

# MULTIDIMENSIONAL MOTION CAPTURE USING DOPPLER ULTRASOUND

by  
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the requirements of the Sally McDonnell Barksdale Honors College.

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## **ABSTRACT**

Ultrasonic waves are used to measure the velocity of a target object by measuring the Doppler shift of the reflected waves. In this work, ultrasonic Doppler Sonar (UDS) was used to measure the velocity of objects, including a pendulum and a battery on a turntable. The investigation focused on developing a method to measure motion in two and three dimensions, for applications in gait analysis and sports motion capture. By using multiple ultrasonic transducers and novel data processing techniques, the UDS captured motion in two and three dimensions. In order to test the accuracy of the velocity and position measurements, the UDS was compared to Dartfish, a video motion capture system. Ultrasonic Doppler successfully captured the motion of a pendulum in one dimension and a battery on a turntable in two and three dimensions, but some limitations arose depending on the target object's shape, material, and velocity. The UDS and Dartfish measured the maximum velocity of a pendulum theoretically found to be 0.62 m/s as 0.60 m/s and 0.60 m/s respectively. To test 2D motion capture, the displacement of a battery traveling on a rotating turntable was measured. The orthogonal diameters were measured to be 12.4 cm (UDS) and 12.5 cm (Dartfish) for the x-direction and 12.4 cm (UDS) and 12.6 cm (Dartfish) for the y-direction.

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## LIST OF SYMBOLS AND ABBREVIATIONS

UDS – ultrasonic Doppler sonar  
FM – frequency modulated  
STFT – short-time Fourier transform  
FFT – fast Fourier transform  
 $c$  – speed of sound in air  
 $m$  – mass  
 $g$  – acceleration due to gravity  
 $h$  – height  
 $v_f$  – final velocity  
 $f$  – frequency  
 $f'$  – detected frequency  
 $f_d(t)$  – frequency of Doppler shift  
 $v_s$  – velocity of object  
 $v_D$  – velocity of detector

## **1. Introduction**

Ultrasonic waves are used to measure the velocity of a moving object by measuring the Doppler signature generated by the object. There are many different applications for this ultrasonic motion capturing system, including gait characterization and physical therapy exercises. The purpose of the following experiments is to test the UDS method for measuring motion in two dimensions. In addition, this thesis seeks to validate previous work demonstrating the accuracy of the ultrasonic Doppler sonar.

The leg swing motion during walking has been measured using UDS to create a spectrogram using a short-time Fourier Transform of the frequency modulated (FM) return signal.<sup>1</sup> Later, Marshall Bradley developed a model using UDS to extract gait parameters from the spectrogram.<sup>2</sup> Additionally, Asif Mehmood demonstrated four different methods of processing the ultrasound data, and for this work, the digital baseband demodulation of reflected signal method is used.<sup>3</sup> At the Mid-South ASA meeting in 2013, Rasheed Adebisi presented data from UDS experiments measuring the velocity of a pendulum<sup>4</sup>. The following experiments validate the measurements in Adebisi's work and demonstrate a method of determining motion in two and three dimensions.

In the first experiment, the velocity measurements of LoggerPro, an ultrasonic rangefinder, and Dartfish, a video analysis software, are compared. The purpose of this experiment is to demonstrate examples of current velocity determination methods and to emphasize the differences between these methods and UDS. The UDS system for determining motion is introduced with several



accompanying experiments, including a comparison to and a demonstration of the accuracy and limitations of the method in one, two and three dimensions. The two-dimensional motion capture system is tested by measuring the velocity and position of a battery moving in a circle on a rotating turntable. Finally, the paper concludes with a demonstration of the UDS system's ability to capture motion in three dimensions.

## **2. Dartfish**

Dartfish ProSuite 6.0 (Dartfish) uses digital video to capture motion in two dimensions and is used to validate the accuracy of the UDS measurements. Dartfish is the top of the line two dimensional video analysis product and performs well compared to the gold standard of motion capture, the three dimensional Vicon System.<sup>5</sup> There are a wide variety of Dartfish applications, including sports training and gait analysis. Dartfish works by using video analysis software to capture motion parameters. In order to measure the velocity of an object, Dartfish software tracks user-selected markers on the object as groups of pixels from frame to frame to determine the distance traveled by the object in the x and y directions. The software uses a measured reference distance in the plane of motion to determine the distance traveled by the object. The software can obtain data in one dimension in both the x and y direction as well as in the two dimensional plane.

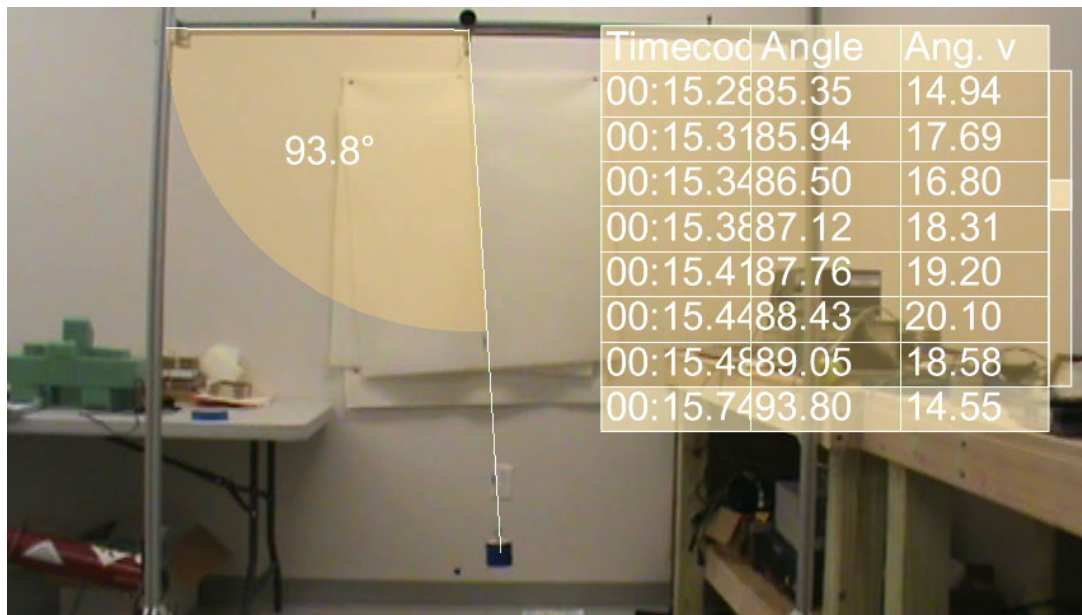


Figure 1: Dartfish video analysis software snapshot. As the pendulum oscillates, Dartfish tracks the contrast in the pixels at the pendulum to be able to measure the position. The related data is put into a graph on screen as it is automatically calculated.

## 2.1 Dartfish Method of Determining Position

The Dartfish method for determining position tracks the pixelated image of the object from frame to frame and gives its displacement from a set origin in x and y coordinates. The object must have a distinct marking in order for the Dartfish software to be able to track the contrast in the pixels. During analysis, a tracking marker must be manually placed on the target object. The software automatically tracks the object from frame to frame until the end of the recording. The displacement of the object between frames, along with the associated time, was recorded into a table as shown in Figure 1. The distance traveled by the target object is determined by comparing the on-screen displacement to a reference distance in the plane of the motion. Sometimes the automatic tracking loses the target object and starts to track another object. The tracking marker must be replaced manually

by the user when it loses the target object, so the video must be viewed frame by frame to make sure that the automatic tracker stays on the object. The software can separate the x and y position data in order to get position measurements in one dimension. The one-dimensional position is limited to the vertical and horizontal axes of the camera image.

### *2.2 Dartfish Method of Determining Velocity*

The Dartfish software converts the displacement into velocity by dividing the displacement by the time elapsed between frames. In addition to finding the total velocity of the moving object, the velocity vectors in the x and y directions are found separately.

## **3. Comparison of Dartfish with LoggerPro**

The position and velocity of an object in one dimension can be determined by using an ultrasonic rangefinder. The ultrasonic rangefinder sends out a pulse of ultrasound towards an object and receives a reflected pulse from the object. The object's distance from the ultrasonic rangefinder can be determined by measuring the time it takes for the pulse to travel to the object and back, multiplying it by the speed of sound in air (343 m/s), and dividing by two to account for the wave traveling the unknown distance twice. LoggerPro software uses the difference between the consecutive distances over time in order to determine the velocity of the object.

### 3.1 Experimental setup for comparison of Dartfish and LoggerPro

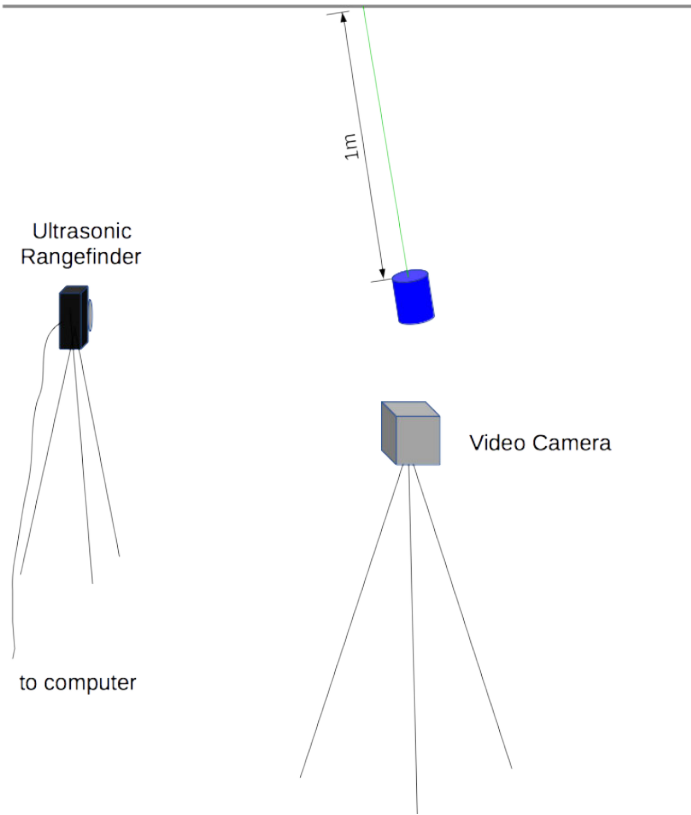


Figure 2: Schematic of the experimental setup comparing Dartfish and LoggerPro. The pendulum swings in the frontal plane of the Ultrasonic Rangefinder, allowing it to capture the velocity of the pendulum using pulsed ultrasound. The video camera is positioned in the sagittal plane to measure the motion of the pendulum as it oscillates.

The LoggerPro ultrasonic range finding method for determining linear velocity was compared to the Dartfish method. The ultrasonic rangefinder used in this experiment emits pulses of ultrasound from a vibrating gold foil into a conical area that is  $15^{\circ}$  to  $20^{\circ}$  from a line extending to the target perpendicularly from the center of the transducer. The transducer measures motion accurately in the range of 0.3 m to 1.2 m.

The LoggerPro collected data at a rate of 20 Hz. The video camera was placed on a tripod 1.1 m in height and 2.8 m in the sagittal plane as pictured in

Figure 2. The video hardware used in this experiment was the SONY Handycam DCR-SX85 set at 60 frame/sec. The length of the pendulum was 1 m. The LoggerPro rangefinder was placed on a tripod 0.57 m behind the pendulum in the frontal plane at a height of 0.67 m. The pendulum started at a distance 0.57 m from the LoggerPro rangefinder. This distance was chosen because the pendulum cannot get closer than 0.3 m or the rangefinder will not be able to pick up the motion. The pendulum was released from a horizontal displacement of 0.12 m.

### 3.2 Results

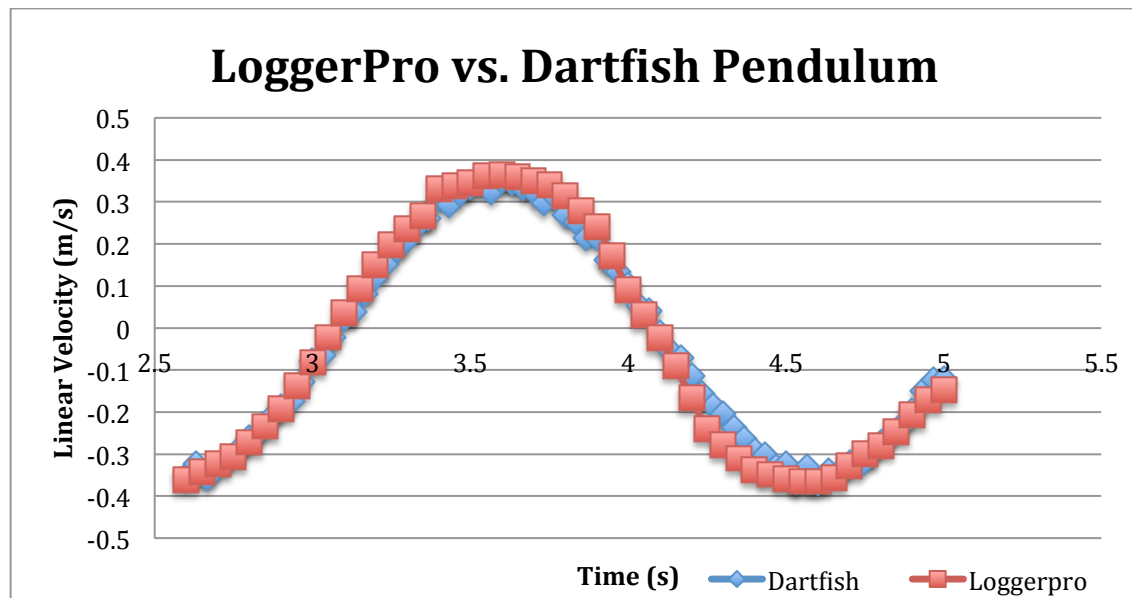


Figure 3: Velocity-Time graph comparing linear velocity measurements using a LoggerPro rangefinder and Dartfish for the motion of the pendulum for just over one period.

The measurements for the velocity of the pendulum were synchronized during analysis by finding the maximum velocity for each graph and synchronizing the times at that point. The velocities matched up well, and at the maximum, LoggerPro values were similar but slightly higher peak to peak than the Dartfish

values. The theoretical value for the maximum velocity of the pendulum was determined by equating the potential energy at the highest point to the kinetic energy at the bottom of the pendulum swing.<sup>6</sup>

$$mgh = \frac{1}{2}(mv_f^2) \quad (1)$$

$$v_f = \sqrt{2gh} \quad (2)$$

The theoretical value for the maximum velocity of the pendulum was 0.37 m/s. From Figure 3, the maximum velocities for UDS and Dartfish were 0.36 m/s and 0.35 m/s respectively. The percent difference between the LoggerPro and the Dartfish data was 3.6%.

### 3.3 Analysis

The results were similar for determining the velocity using LoggerPro and Dartfish. The lower values of the experimental measurements compared to the theoretical values are a result of air resistance, friction, and experimental error by not being able to release the pendulum from exactly 0.12 m.

A drawback of the LoggerPro method includes the minimum distance away from the rangefinder required to determine the motion. This minimum distance requirement occurs because the rangefinder switches from sending mode to receiving mode, and the sound returns to the rangefinder too quickly for it to switch to receiving if the object is closer than 0.3 m. Also, the rangefinder does not perform well as the object gets farther away from the rangefinder. The user's manual recommends determining an object's motion less than 1.2 m away from the rangefinder. Therefore, the usefulness of the rangefinder is limited. Many times the

LoggerPro lost track of the object and began taking data from a stationary object in the background. This error's prevalence required numerous trials in order to get an accurate velocity graph.

#### 4. Ultrasonic Doppler Sonar

The UDS system measures the Doppler frequency shift of continuous wave ultrasound scattered by a moving object to obtain the velocity of the moving object.<sup>3,7</sup> The signal received from the moving surface is frequency modulated (FM) due to the Doppler effect, and the frequency shift of the received signal is directly proportional to the moving velocity of the target. The relationship is expressed according to the general Doppler effect as:

$$f' = f \frac{c \pm v_D}{c \mp v_S} \quad (3)$$

where  $f$  is the emitted frequency,  $f'$  is the detected frequency,  $c$  is speed of sound,  $v_D$  is the speed of the detector relative to the air, and  $v_S$  is the speed of the object relative to the air.<sup>6</sup>

For active Doppler sonar, the frequency is Doppler shifted twice for both the outgoing signal and the returning signal.<sup>8</sup> For an object moving towards a stationary detector, the outgoing signal Doppler frequency using Equation 3 with  $v_D = 0$  and using a minus sign in the denominator because the object is moving towards the detector is given below:

$$f' = f \frac{c}{c - v_S} \quad (4)$$

The returning signal is also Doppler shifted but now the moving object is the source and in the frame of reference of the moving object, the detector is moving with a velocity  $v_s$  towards the source. Using the Doppler shifted frequency from Eq. 3 the new Doppler shifted frequency is shown below:

$$f'' = f' \frac{c+v_s}{c} \quad (5)$$

by substituting using Eq. 4

$$f'' = \left( \frac{c}{c-v_s} \right) \left( \frac{c+v_s}{c} \right) f \quad (6)$$

simplifying and dividing the numerator and denominator by c gives:

$$f' = \left( \frac{1+v_s/c}{1-v_s/c} \right) f \quad (7)$$

Simplifying this equation using the assumption that  $v$  is a small fraction of  $c$ , the denominator can be expanded in a binomial series and multiplied by the numerator<sup>9</sup>:

$$f' = \left( 1 + \frac{v}{c} \right) \left( 1 - \frac{v}{c} \right)^{-1} f \quad (8)$$

$$f' = \left( 1 + \frac{v}{c} \right) \left[ 1 + \left( \frac{v}{c} \right) + \left( \frac{v}{c} \right)^2 + \dots \right] f \quad (9)$$

$$f' = \left[ 1 + 2 \left( \frac{v}{c} \right) + 2 \left( \frac{v}{c} \right)^2 + \dots \right] f \quad (10)$$

By discarding all second-order and higher terms in  $(v/c)$ :

$$f' = \left[ 1 + 2 \left( \frac{v}{c} \right) \right] f \quad (11)$$

Using  $f_d(t)$  as the frequency of Doppler shift or  $f' - f$  gives:

$$f_d(t) = \frac{2f}{c} v(t) \quad (12)$$



The velocity of the object in terms of the frequency of the Doppler shift is:

$$v(t) = f_d(t) \frac{c}{2f} \quad (13)$$

#### 4.1 Determining Motion in One Dimension using Doppler Ultrasound

The ultrasonic transducer used in the following experiments is pictured in Figure 4. The resonance frequency of these transducers is 40kHz with a bandwidth of 2kHz (at -6dB) and a directivity of 60° (at -6dB). The transducer contains two piezoelectric sensors. One continuously sends out signal, while the other sensor continuously receives signal. The signal that returns to the co-located transducer from the moving target is frequency modulated (FM) due to the Doppler effect.



Figure 4: Image of the ultrasonic Doppler Transducer on a tripod. A piezoelectric sensor, behind the mesh circle covering on the left, is the transmitter and emits continuous wave ultrasound at a carrier frequency of 40 kHz. The piezoelectric sensor on the right is the receiver and oscillates based on the returned ultrasonic waves, converting the ultrasonic signal into an electrical signal, which is then analyzed by a computer.

## Diagram of Ultrasonic Doppler Sonar Electronics

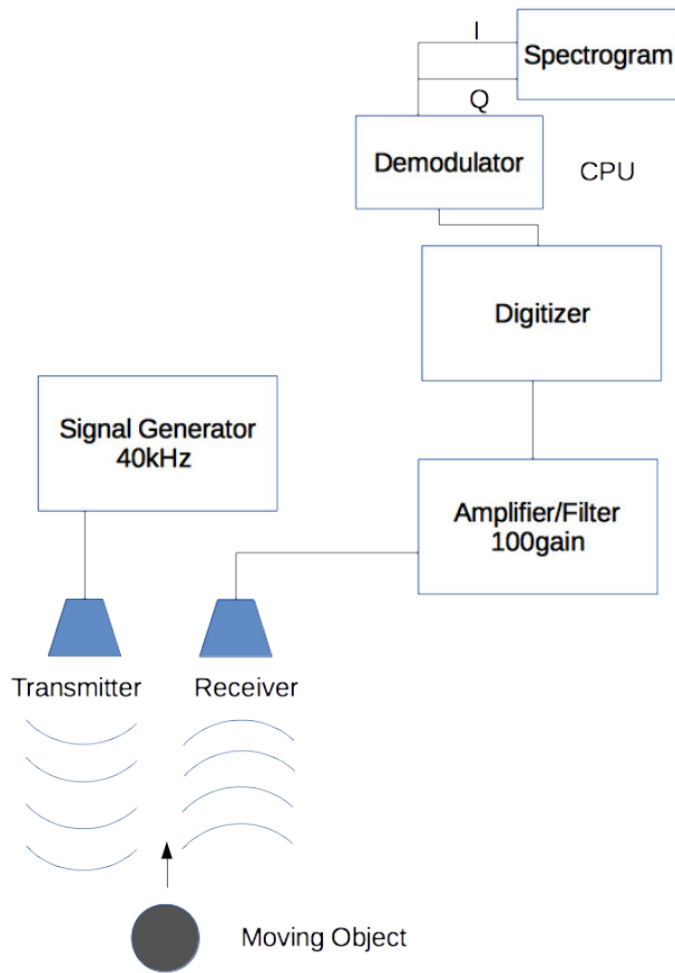


Figure 5: Diagram of the electronics setup for UDS. The signal generator sends a 40 kHz sine wave to the Ultrasonic transmitter, creating the 40kHz carrier frequency. The FM signal returns to the receiver and is amplified and digitized before being demodulated. The I and Q data is then converted into a spectrogram

For the one-dimensional motion experiment, the electronics setup is shown in Figure 5. The signal generator was a multifunction synthesizer (8904A Multifunction Synthesizer DC-600 KHz Hewlett-Packard). Using this signal generator the transducer emitted a 40 kHz continuous sine wave ultrasound signal. The receiver was connected to an amplifier (Stanford Research Systems Model SR560 Low-Noise Preamplifier), which increased the gain by a factor of 100. The

signal was then sent to the digitizer, which for this experiment was a Wavebook. The Wavebook digitized the audio file, and then the audio file was read into Matlab, where the signal was mixed with the original signal to demodulate the signal to I and Q data. Finally, the I and Q data was used to make a spectrogram as shown in Figure 6 (See Appendix A for explanation).

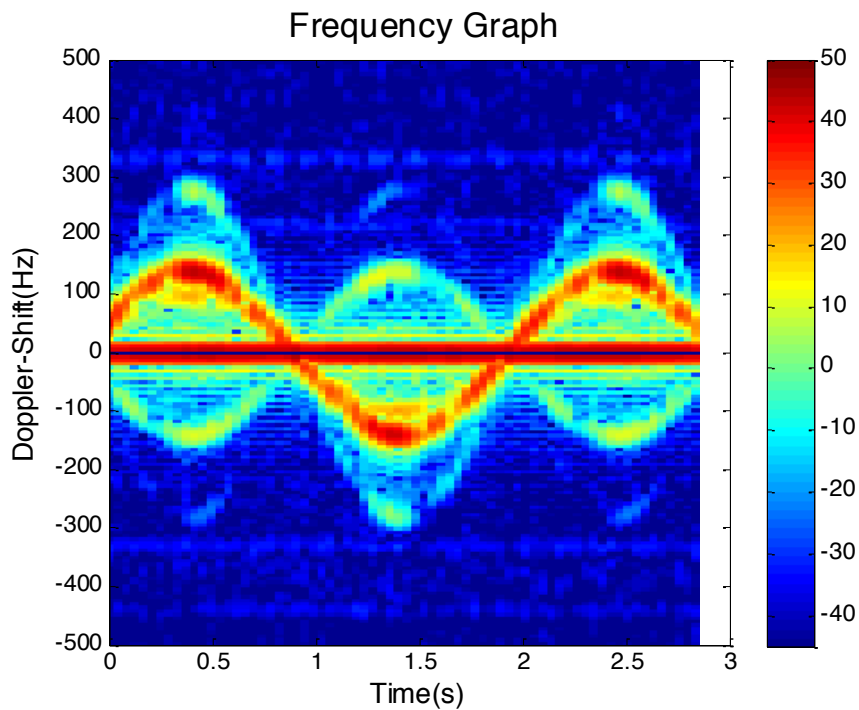


Figure 6: Spectrogram of the pendulum released from 20 cm. This spectrogram shows 1.5 periods. The y-axis has been left in Doppler shifted frequencies.

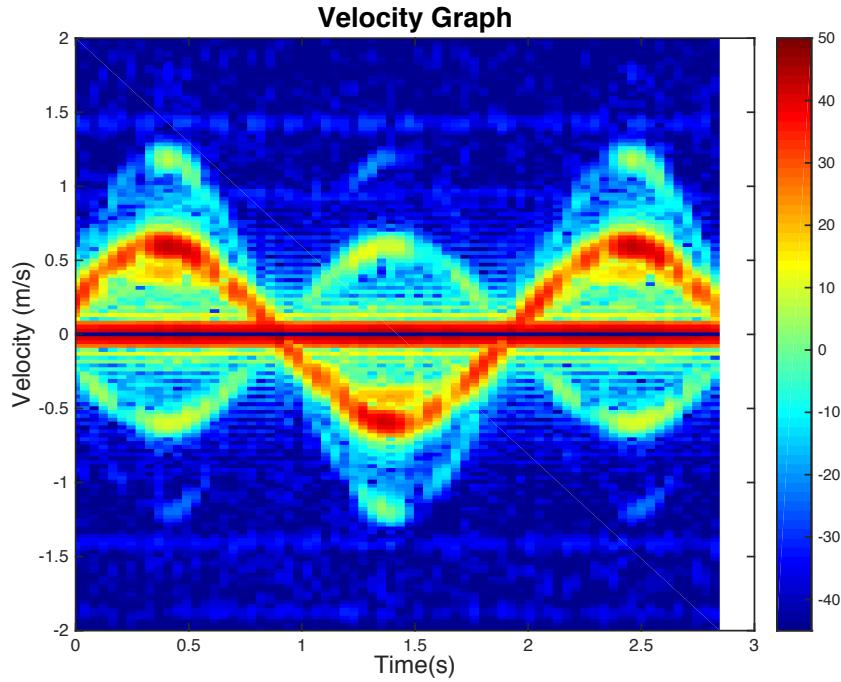


Figure 7: This spectrogram is the same as in Figure 6 with the y-axis converted from Doppler shifted frequency to target object velocity.

A sampling rate of 100 kHz was used to collect the data, and a series of fast Fourier transforms with a window size of 8,192 points and an overlap of 4,096 points were used to create a spectrogram, showing the evolution of the frequency shifts with time (see Appendix B for code). Figure 6a shows an example of the spectrogram. The coloration of the pixels in the spectrogram corresponds to the intensity of the ultrasonic signal received by the transducer. The highest intensity return signal, ignoring the intense band around the carrier frequency, is the signal that corresponds to the motion of the target object. For Figure 6, the target object's Doppler frequency shift is the red sine shaped curve centered at 40kHz. Figure 6 shows the Doppler frequency shift with respect to time, and Figure 6b shows the velocity of the target object with respect to time. The velocity of the object is

determined by using the frequency shift due to the Doppler effect by Equation 13 where  $v(t)$  is the linear velocity of the object,  $c$  is the speed of sound,  $f$  is the carrier frequency, and  $f_d(t)$  is the Doppler shift. Converting the Doppler frequencies to velocities creates the spectrogram in Figure 7.

To determine the velocity of the target object, a code was developed to pick out the highest intensity signal for each column of the spectrogram (see Appendix C for code). The data from the spectrogram was graphed with the intensity of the return signal as the y-axis and the frequency as the x-axis. This peak frequency corresponded to the Doppler frequency shift of the target object. The peak was tracked over time to create a velocity vs. time graph. The high intensity values around 0 m/s were the reflections of the carrier frequency off of stationary objects nearby. The high intensity band at 0Hz was usually the highest peak, so it was removed or ignored to track the desired peak. The velocity was then plotted vs. time (see Figure 8) and the curve was integrated in order to determine the displacement of the target (see Figure 9).<sup>10</sup>

One difficulty in determining the correct velocity and position of the target is the band of frequencies around the carrier frequency that results from the carrier frequency echoing off of the non-moving objects in the field of vision of the transducer. One way to avoid this erroneous signal is to subtract out the band at 40 kHz. The loss of frequencies around the carrier frequencies causes low velocities to be lost, so the velocity graphs show a gap or a blind spot from -0.05 m/s to 0.05 m/s. Since the velocity that is missed is small it does not have a dramatic impact on the position data.

#### *4.2 Determining the Motion of a Pendulum Using Doppler Ultrasound*

In order to compare the accuracy of the UDS to the Dartfish, the motion of a pendulum was measured by both systems simultaneously.

##### *4.2.1 Experimental Setup for comparison of Dartfish and Ultrasound using Pendulum*

The setup for the experiment was the same as Figure (1) except an Ultrasonic Doppler transducer was used instead of a LoggerPro rangefinder. A metal cylinder with dimensions of 48 mm in height and 53 mm in diameter was attached to a meter long string anchored to a fixed metal frame to create a pendulum. The cylinder was 35 inches off the ground. The distance from the axis of rotation of the pendulum to the top of the cylinder was 1.02 meters. The camera (Panasonic AG-HMC150P Camcorder) was placed six feet away from the pendulum in the sagittal plane on a tripod with a height of 55 inches. The camera captured video at 60 frames/sec. An ultrasonic transducer was placed in the frontal plane in order to measure the motion of the cylinder. The transducer was on a tripod that was 33 inches of the ground. In order to synchronize the two data acquisition systems, a Keysight 33500B Series Waveform generator was used to send a pulse to both an LED light and the pulse trigger in the Wavebook. The Wavebook was set to trigger at 2 V with a minimum width of .5 seconds. For the first experiment, the cylinder was released at a horizontal displacement of 20 cm.

#### 4.2.2 Results

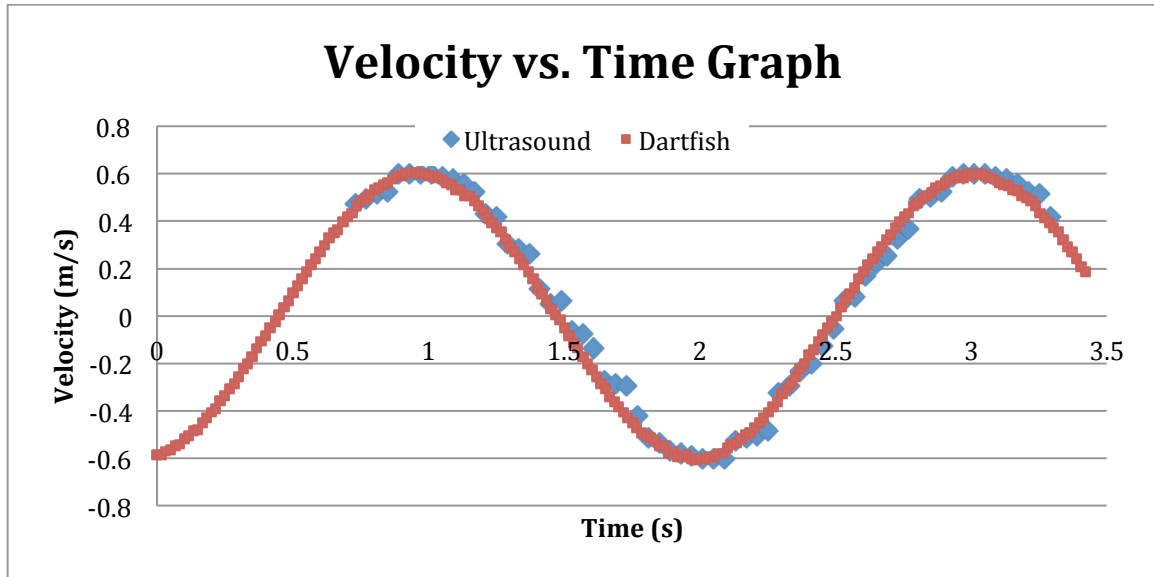


Figure 8: Velocity vs. Time Graph of Pendulum released from 20 cm.

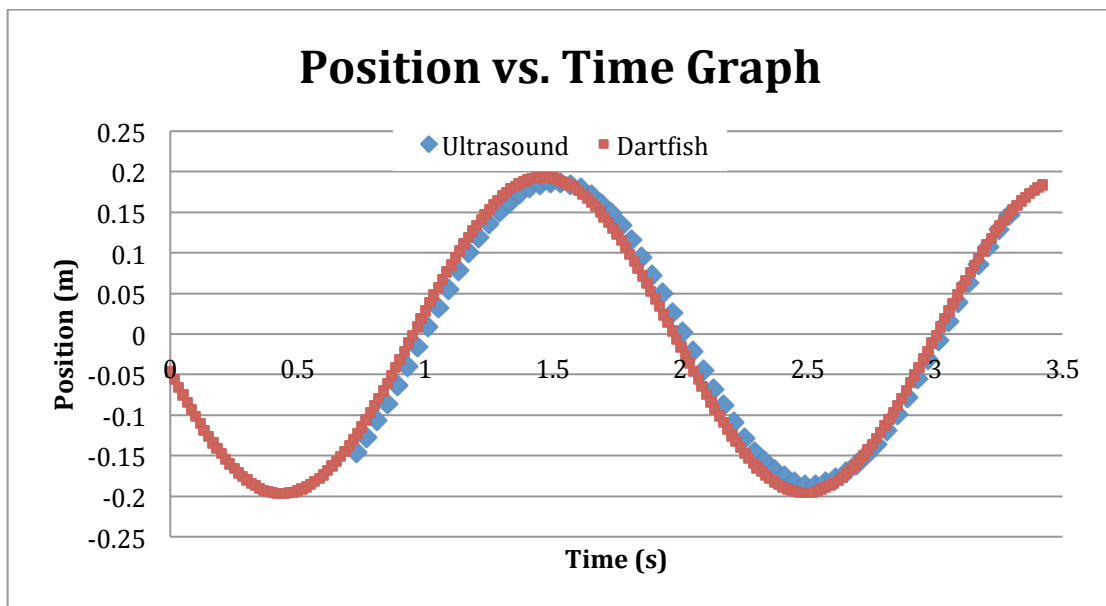


Figure 9: Position vs. Time graph of Pendulum released from 20 cm

#### 4.2.3 Analysis

The ultrasound data had a delay so the Dartfish and Ultrasound were synchronized using a delay of 0.69 seconds. The delay was due to a 0.5 second minimum gate width set in the Wavebook trigger. The remaining time resulted from the time delay in the creation of the spectrogram using the window and overlap. The more points taken in the FFT, the shorter the delay time is between the ultrasound and Dartfish.

The cause of the ghost signals in the spectrogram in Figure 6 is multipath. Multipath occurs when the ultrasonic signal bounces off the moving object and then off of a wall or other stationary object. The signal then bounces back off of the moving object, which causes the ghost signal to be twice the original signal. Similarly, if the ultrasound bounces off of a wall or object behind the object before reflecting off of the target object, it gives a ghost signal that will be the negative of the original signal. Foam was placed on walls and the frame that held the pendulum to reduce the amount of multipath signal. The foam absorbs the ultrasonic waves and reduces the amount of reflection back to the transducer.

As shown in Figure 8, the velocity data for both the Dartfish and Ultrasound method are extremely similar. The ultrasound data is not as smooth of a sine curve as the Dartfish data and this is a result of the Dartfish system having a higher sampling rate. In addition, small variances from Dartfish develop as the peak frequency is picked out of each FFT with limited frequency resolution. From Figure 9, the position data for the pendulum is closely matched between the two systems. The data for the ultrasound is smoother as the result of integrating using Matlab.



The theoretical value of the maximum velocity of the pendulum was determined using the same method as in Section 2.2 and is calculated to be 0.63 m/s. The Dartfish maximum velocity was measured to be 0.60 m/s and the Ultrasonic Doppler was 0.60 m/s. The percent difference between the UDS and the theoretical was found to be 4.9%. As in the LoggerPro experiment, the measured velocities were slightly lower than the theoretical maximum velocity due to air resistance and friction during the motion of the pendulum. The UDS and Dartfish were extremely similar in this experiment, demonstrating the UDS system's accuracy in determining velocity in one dimension.

## **5. Determining Motion in Two Dimensions using Ultrasonic Doppler Sonar**

For determining motion in two dimensions, two ultrasonic transducers are placed orthogonal to each other to combine the two one-dimensional motions into two dimensional motion. The electronic setup is the same as in Figure 5, but there are two transducers, two amplifiers and two spectrograms (see Appendix D for creation of spectrograms). To reduce crosstalk between the transducers, one of the transducers emits a 39500 Hz signal and the other transducer emits a 40500 Hz signal. The difference between the signals is large enough to capture the frequency shifts of the reflections of both transducers. The one-dimensional method of determining velocity and position was used for both sensors. The ultrasonic waves in this experiment were assumed to be acting as plane waves instead of spherical waves. The x and y positions were graphed to generate a two dimensional image of the motion of a battery rotating on the turntable (see Appendix E for code).

## 5.1 Comparison of UDS and Dartfish for 2-D Motion using a Turntable

### 5.1.1 Experimental Setup

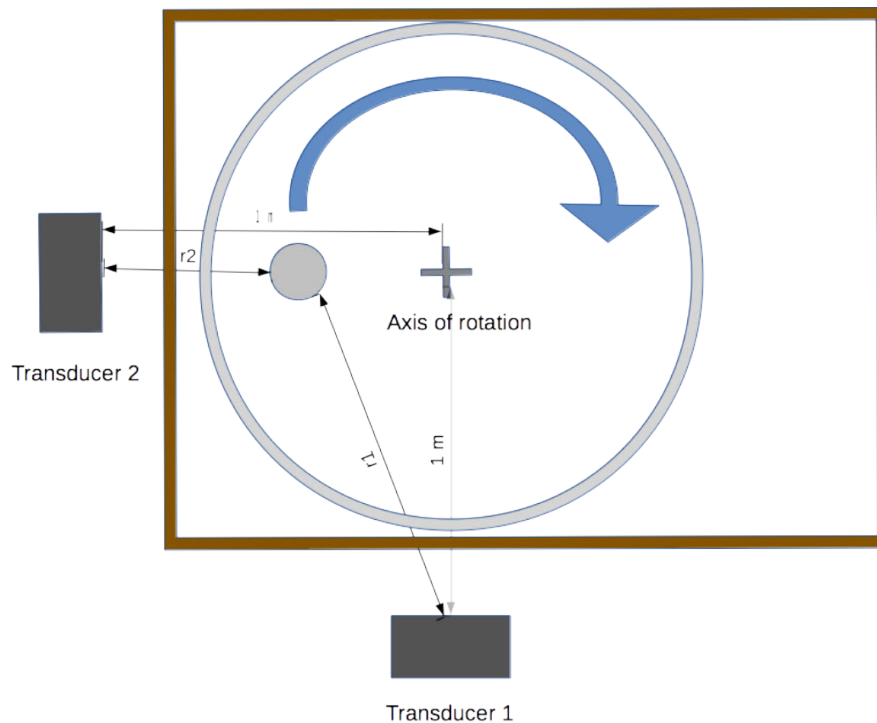


Figure 10: Diagram of the 2D turntable experiment with a D battery, comparing Dartfish and Ultrasound, as seen from the view of the video camera above. The transducers are placed at the same height as the D battery perpendicular to one another. The battery moves in a circle around the axis of rotation as the turntable rotates at 33 rpm.

A turntable was used to test the accuracy of the UDS system in two dimensions. For this experiment, a D battery was placed on a turntable which was on a table. The D battery was selected for this experiment because it has right circular symmetry and returns the same signal as it rotates. The height of the top of the battery from the ground was 35 inches. Two ultrasonic transducers were placed on tripods at a height of 35 inches. The transducers were placed a meter from the

axis of rotation and orthogonal to one another, as shown in Figure 10. Transducer 1 emitted a signal of 39500 Hz and transducer 2 emitted a signal of 40500 Hz.

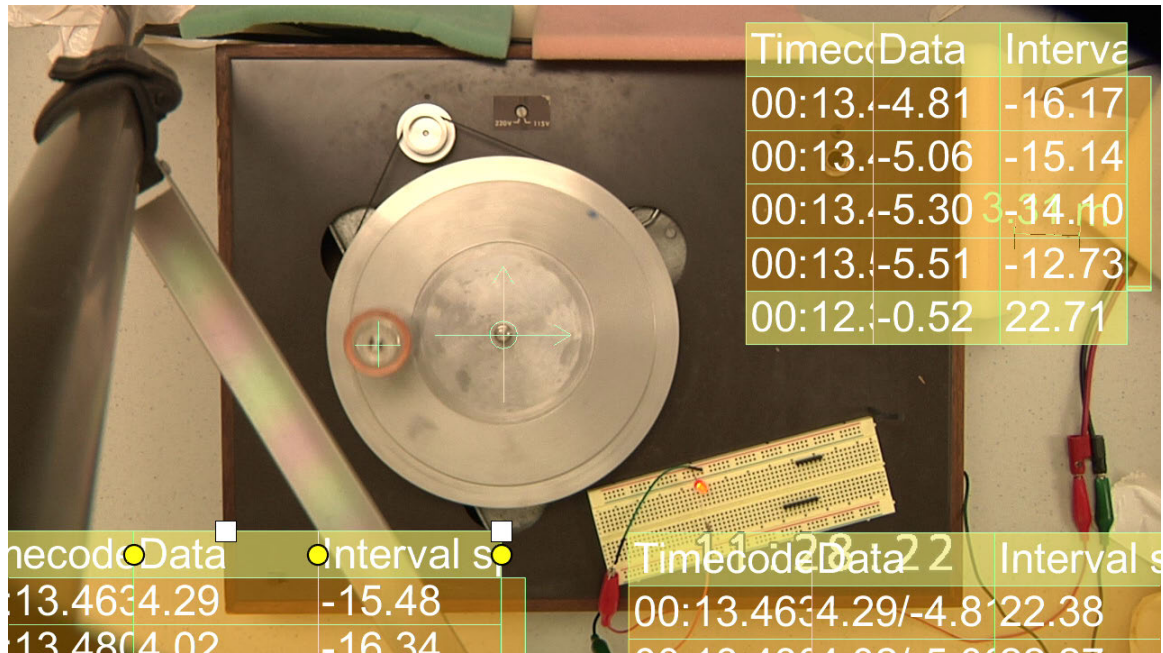


Figure 11: Dartfish Snapshot from camera used to determine the motion of the battery in two dimensions. The Dartfish software tracked the contrast in pixels of the x at the center of the top of the D battery. The light at the bottom right side of the turntable is used to synchronize the ultrasound data to the video camera data.

The camera (Panasonic AG-HMC150P Camcorder) was placed on a tripod directly above the turntable's axis of rotation to acquire data in two dimensions (see Figure 11). In the experiment, the battery was placed with its center at a distance of 6.4 cm from the axis of rotation of the turntable. For Dartfish analysis, the diameter of the battery (3.3 cm) was used as a reference distance. The center of the turntable was set as the origin with the positive y-axis pointing up and the positive x-axis pointing right. A marker with two quarter circles was placed on the center of the battery to ensure that Dartfish obtained accurate data. Dartfish tracks objects using contrast between pixels, so markers are necessary for accurate motion capture. In

addition, foam covered all surfaces in the field of view of the transducers to reduce the amount of multipath. A time delay of 0.271 seconds was used to synchronize the data. The minimum gate width of the Wavebook was set to 0.1 seconds and the remaining delay was a result of the calculation of the spectrogram.

### 5.1.2 Spectrogram Results

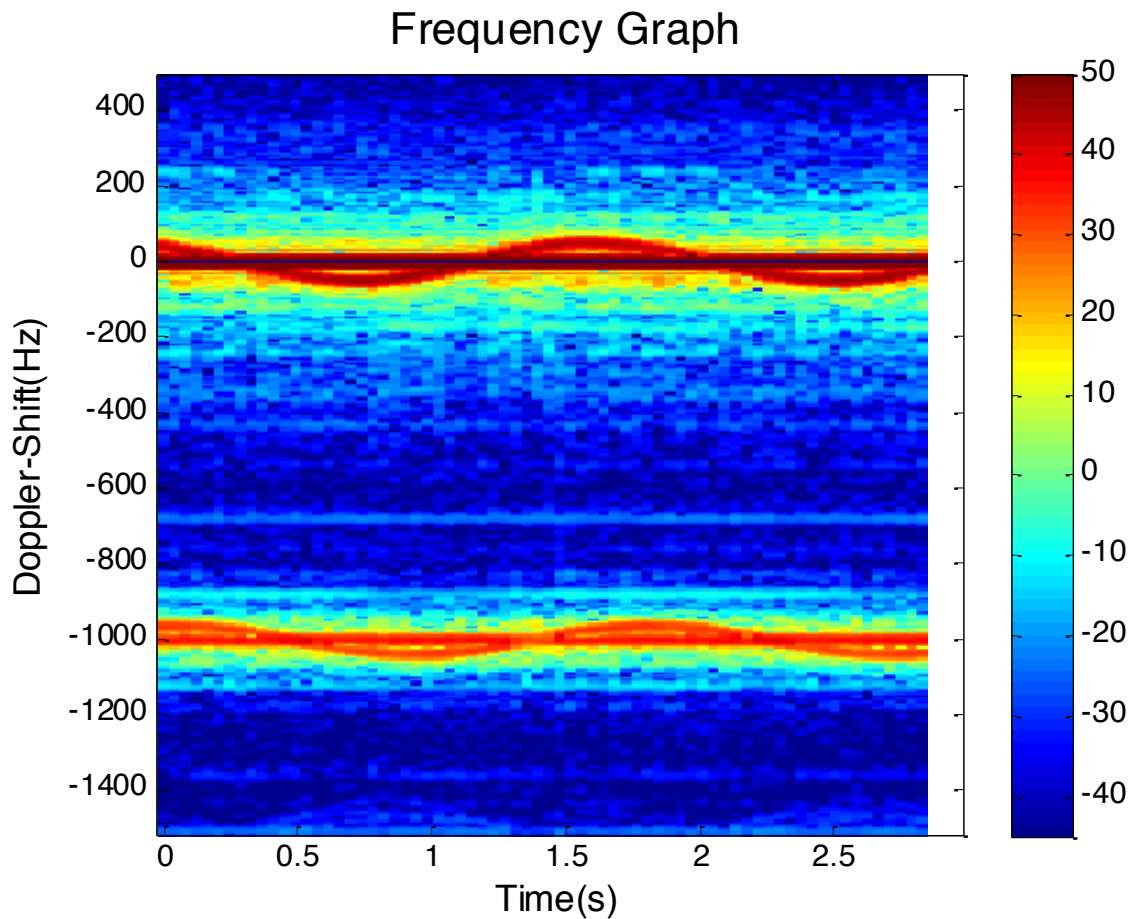


Figure 12: Spectrogram for Transducer 1. Two signals are seen in this figure because the transducers are set at different carrier frequencies 1000 Hz apart. The signal centered at 0 Hz is the desired signal from Transducer 1.

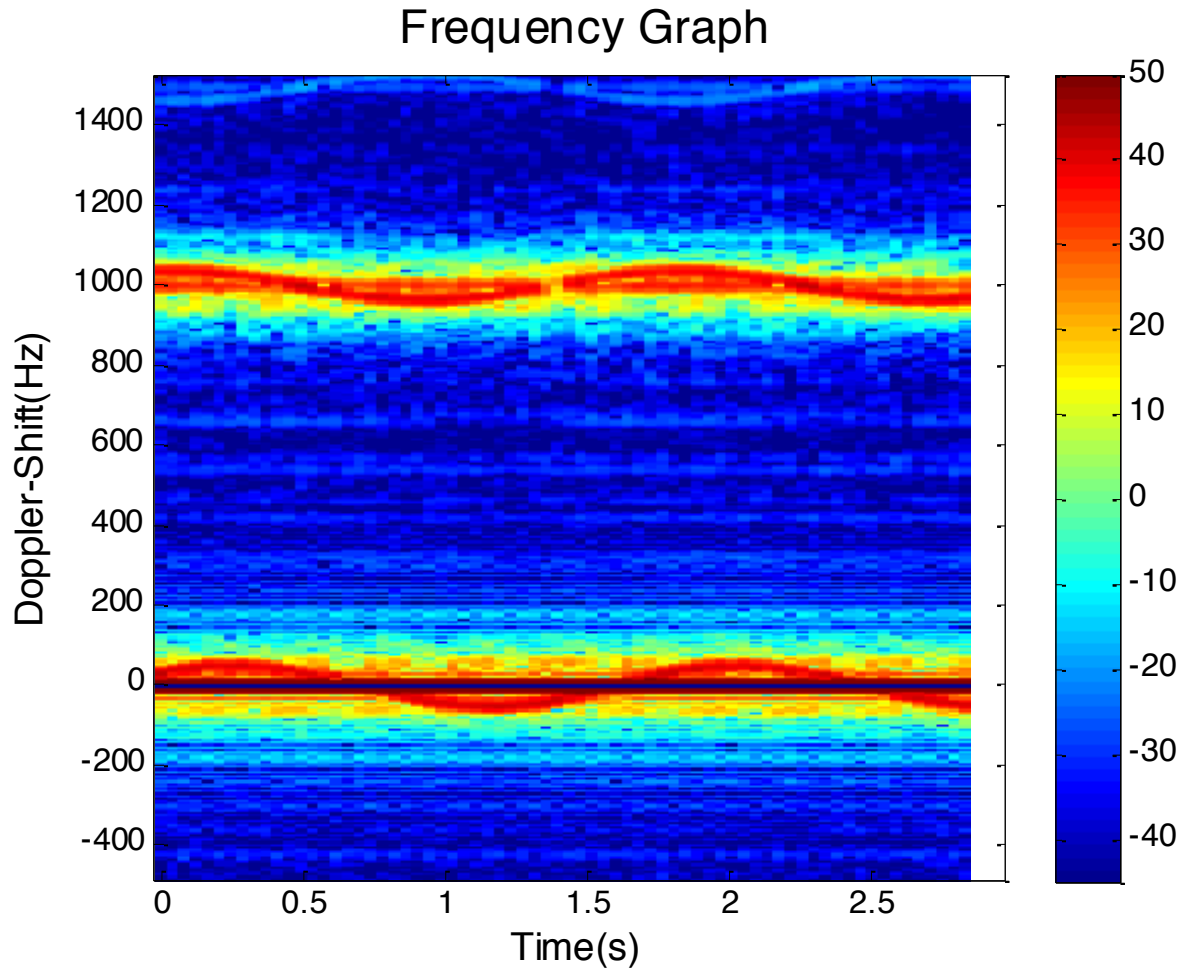


Figure 13: Spectrogram for Transducer 2. As in Fig. 12, two signals can be seen in this spectrogram. The target signal in this spectrogram is the signal centered at 0 Hz.

#### 5.1.3 Analysis of the Two-dimensional Spectrogram Data

In Figure 12, two signals were present at each carrier frequency since both transducers emitted a signal. The signal from transducer 1 reflected off of the moving object and returned back to Transducer 1. The signal from Transducer 2 reflected off of the object and traveled perpendicularly to Transducer 1, causing the second signal to appear on the spectrogram in Figure 12. The reflected signal returning to the original transducer has a higher intensity return signal than the

orthogonally reflected signal. Figure 13 shows the spectrogram from Transducer 2 with the orthogonally reflected signal (sent out at 40.5 kHz) greater than the directly reflected signal (sent out at 39.5 kHz).

#### 5.1.4 2-D Turntable Velocity and Position Results

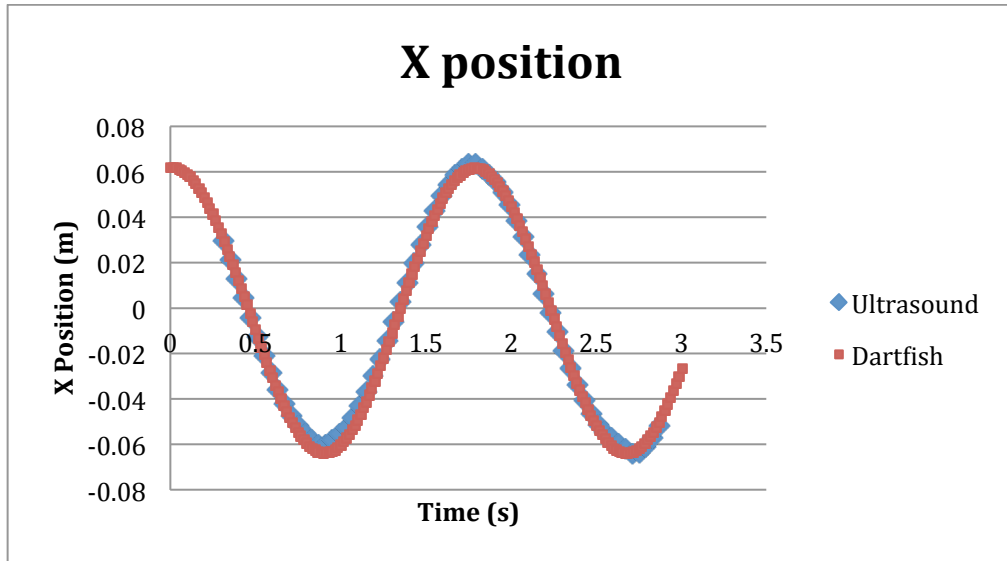


Figure 14: Position v. Time Graph of D battery in the X-direction

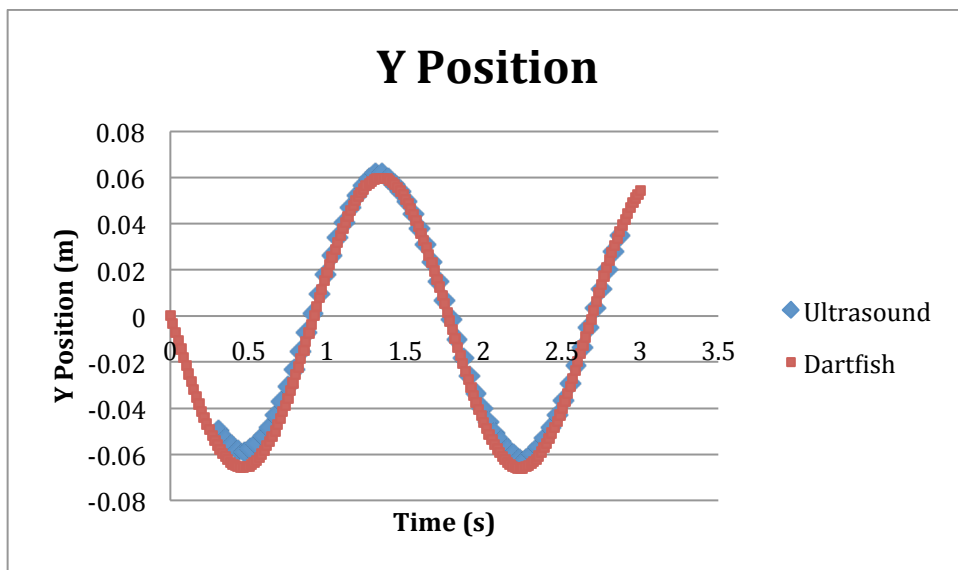


Figure 15: Position vs. Time Graph of D battery in the Y-direction

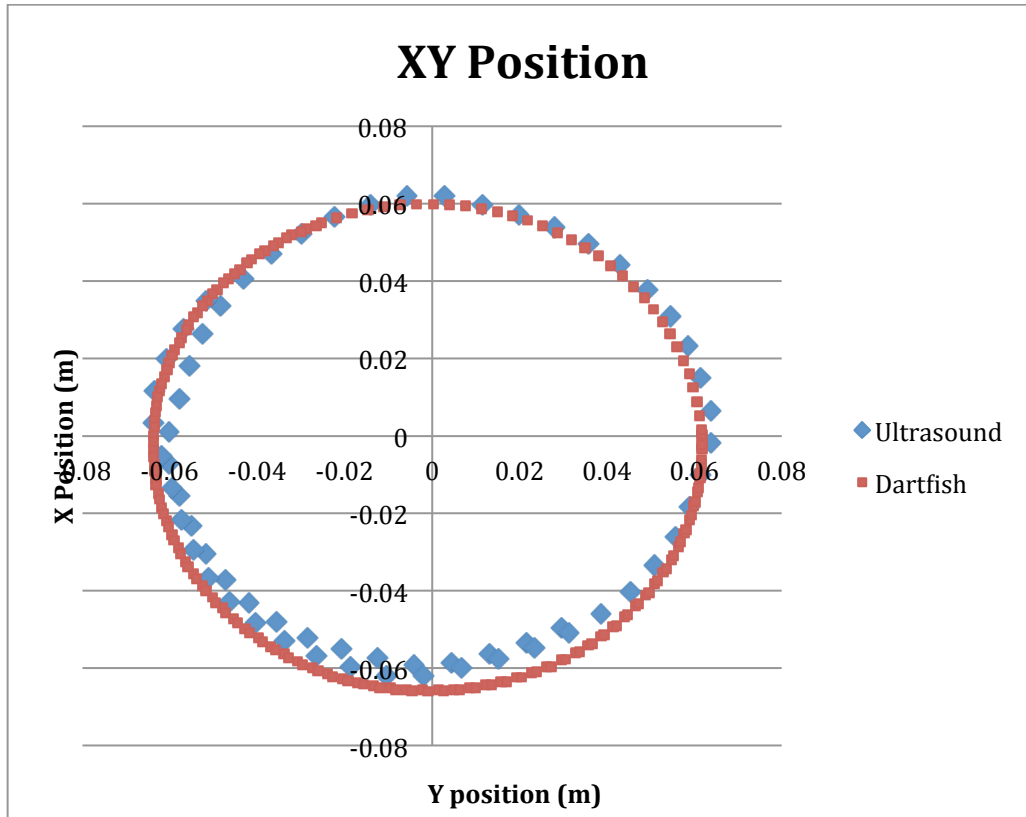


Figure 16: 2D turntable experiment. Position vs. Time Graph in x and y directions

The velocity vs. time data for both x and y velocities has a gap from  $-0.05 \text{ m/s}$  to  $0.05 \text{ m/s}$  that is caused by the signal becoming lost in the carrier frequency band that is centered at  $0 \text{ Hz}$ . The gap was more prominent in this experiment than the pendulum experiment because the turntable moved at a lower speed. The blind spot from  $-0.05 \text{ m/s}$  to  $0.05 \text{ m/s}$  makes it difficult to measure target objects that are moving at slow speeds. Since the blind spot occurs at such small velocities, it does not have a major impact on the position vs. time graphs shown in Figures 14 and 15. The UDS system measured the maximum velocity measurements slightly lower than the Dartfish velocity measurements. This discrepancy occurs because the ultrasonic

Doppler method is taking velocity data at 25 Hz while the Dartfish system is taking data at 60 Hz, which allows the Dartfish system to be able to more accurately obtain the higher velocities of the sharp velocity peaks.

The measured diameter of the circular path in the X direction was used to determine the accuracy of the position data from Figure 14. The diameter was calculated by finding the difference between the first minimum and first maximum. The theoretical diameter was calculated by doubling the measured radius (6.4 cm) to get 12.8 cm. The UDS radius measurement was 12.4 cm and the Dartfish measurement was 12.5 cm. The calculated percent difference between the UDS and the Dartfish data was 0.8%, and the percent difference between the UDS and the theoretical was 3.2%.

The diameter measurements for the y-direction were measured by finding the difference between the first maximum and the second minimum. The UDS measurement was 12.4 cm and the Dartfish measurement was 12.6 cm. The percent difference between the UDS and Dartfish was 1.6% and the percent difference between the theoretical and the UDS measurements was 3.2%. The ultrasound diameter was slightly lower than the Dartfish and theoretical diameter because of the smaller peak values obtained in the velocity data.

For the turntable, the center of the axis of rotation can be determined by averaging the maximum and minimum displacement of the target object. The distance of the axis of rotation can be subtracted from the position vs. time graph in order to get the position relative to the axis of rotation centered at the origin.



The off-center Dartfish data from Figure 16 could be the result of the tracking method not maintaining the center of the battery or the camera being at a slight angle relative to the turntable. When the object is closest to both transducers, the velocity and position data is not as accurate. As the object moves closer, the ultrasonic waves begin to act more like spherical waves. The assumption that the waves are behaving like plane waves instead of spherical waves causes the system to be less accurate as the object is close and off-center from the transducers.

## *5.2 Turntable experiments examining the effects of different materials and sizes of objects*

### *5.2.1 Experimental setup*

The setup for this experiment is similar to experiment in Sec. 5.1 except the turntable is on the ground along with transducers and only one transducer is used.

### *5.2.2 Results for Experiments with the Toilet Paper Roll and AA Battery*

Both the toilet paper roll and AA battery velocities were able to be determined using UDS. Since the toilet paper roll is hollow the signal reflects off both the front side of the toilet paper and the back of the toilet paper creating a slightly wider signal. The AA battery, since it has a smaller cross-section than the D battery, returns a weaker reflected signal than the D-battery because there is cross-sectional area from which the ultrasound reflects.

### *5.2.3 Setup for Metal Block experiment*

A metal block (50 mm by 44 mm by 44 mm) was placed on the turntable, which was resting on a table. The ultrasonic transducer was 0.8 m off ground and 1 m away from axis of rotation of the turntable. For this experiment, National Instruments software was used to digitize the data instead of Wavebook.

### *5.2.4 Results*

The metal block presented challenges for determining the velocity due to the sharp edges and flat surfaces of the block. When the block face is directly perpendicular to the direction of the ultrasound, there is a large return signal that extends down to the carrier frequency. This results from the large cross-section presented to the transducer by the block. When the edge of the block is facing the ultrasonic transducer, there is a dramatic drop in the received ultrasound signal due to the geometry of the block deflecting the signal to the left and right instead of back towards the transducer. This experiment demonstrates some of the limitations of the ultrasound motion capture system, especially some objects that have sharp edges and corners.

## *5.3 Measurement of Putter Head during the Putting stroke motion*

Several experiments were run using different kinds of putters to test the effectiveness of the UDS in measuring the velocity and displacement of the putter head during the putting stroke. The setup was similar to the experiment in sec 5.2.1 except instead of measuring the battery on a turntable, I swung a putter and the UDS tracked the motion of the putter head. Different putter head shapes caused

difficulties in picking out the target Doppler shift from the spectrogram, but overall the UDS was very effective at measuring the velocity and two dimensional path of the putting stroke.

#### *5.4 Experiments testing range of ultrasound*

The Ultrasonic transducer was placed at 1m, 2m, and 3m to demonstrate the effect of moving further away from the axis of rotation. The farther the transducer was placed from the turntable, the smaller the signal to noise ratio. This phenomenon occurs because the background reflections remain constant, but the reflection back from the battery is smaller as the transducer is moved further away. The sound pressure level decreases with distance from the source, causing the decrease in the intensity of the returned signal from the desired object.

#### *5.5 Turntable experiments using off-axis Ultrasonic sensors*

The 2D position of a moving object in two dimensions can also be measured by using transducers that are off-axis. In this experiment, transducers were placed at various positions around the turntable to be able to test the accuracy of the method (see Figure 17).

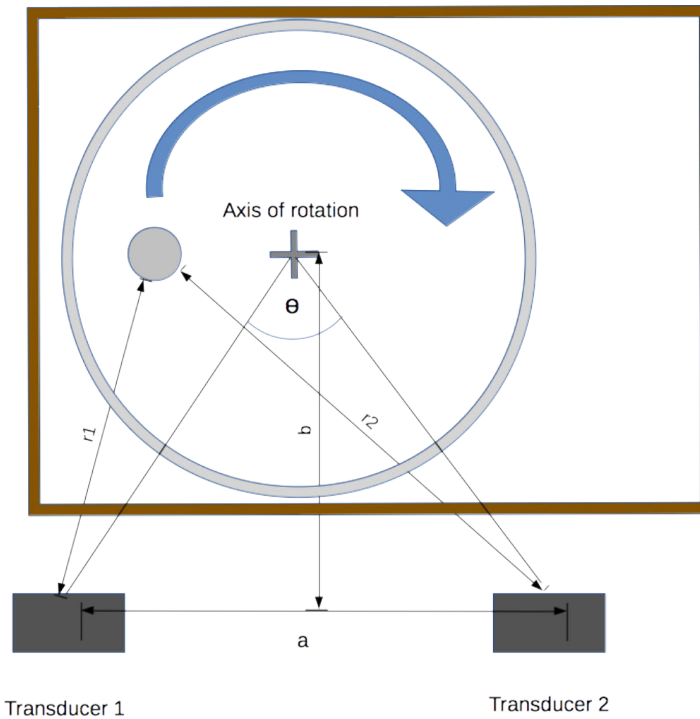


Figure 17: Diagram of setup for off axis transducers. The transducers are placed the same distance away from the axis of rotation but with different distances between the transducer (a). Changing the distance between the transducers changes angle  $\theta$ , which is used to differentiate between the different experiments in this section.

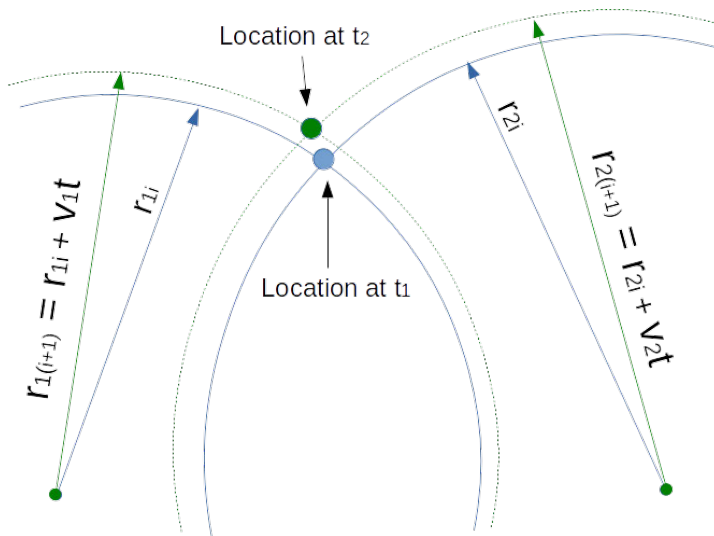


Figure 18: Demonstrates method for determining position in two dimensions using off-axis transducers. The intersection of two circles is used to track the position of the target object

To determine the motion with displaced sensors, the distance from each transducer to the target object must be determined. Since Doppler ultrasound cannot determine the initial position only displacement, the initial position relative to the two transducers must be measured or provided. Once the initial distance from the transducer to the object is found, the displacement is added to find the new position. Since ultrasound sends out spherical waves this distance from the transducer can be thought of as a radius of a circle centered at the transducer passing through the point where the target object is located. Since each transducer has its own distance to the target object, the setup can be viewed as two circles with changing radii as depicted in Figure 18. Using the fact that the intersection of two circles gives two points, and ignoring the intersection point behind the transducers. The position of the target object can be determined by finding the intersection of the two circles. Therefore, the transducers no longer have to be orthogonal to one another, and can be placed at arbitrary locations around the target object (see Appendix F for code). The equation for the intersection of two circles is shown below using the variables defined in Figure 17:

Equations:

$$r_1^2 = [x + (a/2)]^2 + (y + b)^2 \quad (14)$$

$$r_2^2 = [x - (a/2)]^2 + (y + b)^2 \quad (15)$$

Subtract second equation from first equation

$$r_1^2 - r_2^2 = 4(a/2)x \quad (16)$$

$$x = \frac{(r_1^2 - r_2^2)}{2a} \quad (17)$$

Using the x value solved for find y

$$r_1^2 = [x + (a/2)]^2 + (y + b)^2 \quad (18)$$

solve for y

$$r_1^2 - [x + (a/2)]^2 = (y + b)^2 \quad (19)$$

$$y = \sqrt{r_1^2 - [x + (a/2)]^2} - b \quad (20)$$

#### 5.5.1 *Introduction to off-axis transducer experiments*

To test the effectiveness of the off-axis method several experiments were run with transducers placed at varying angles around a turntable. The experimental set up was the same as for the turntable experiment in Sec. 5.1 except instead of being orthogonal or  $\theta=90^\circ$  apart the transducers were placed at  $\theta=45^\circ$ ,  $\theta=22.5^\circ$ , and  $\theta=135^\circ$ .

#### 5.5.2 *Experimental setup transducers displaced at $45^\circ$*

The transducers were placed with  $\theta = 45^\circ$ , 27.5 cm apart ( $a = 27.5$  cm), and 91.44 cm ( $b = 91.44$  cm) from axis of rotation from the axis of rotation. The video camera used in this experiment was a Panasonic AVCCAM AG-HMC150P.

### 5.5.3 Results

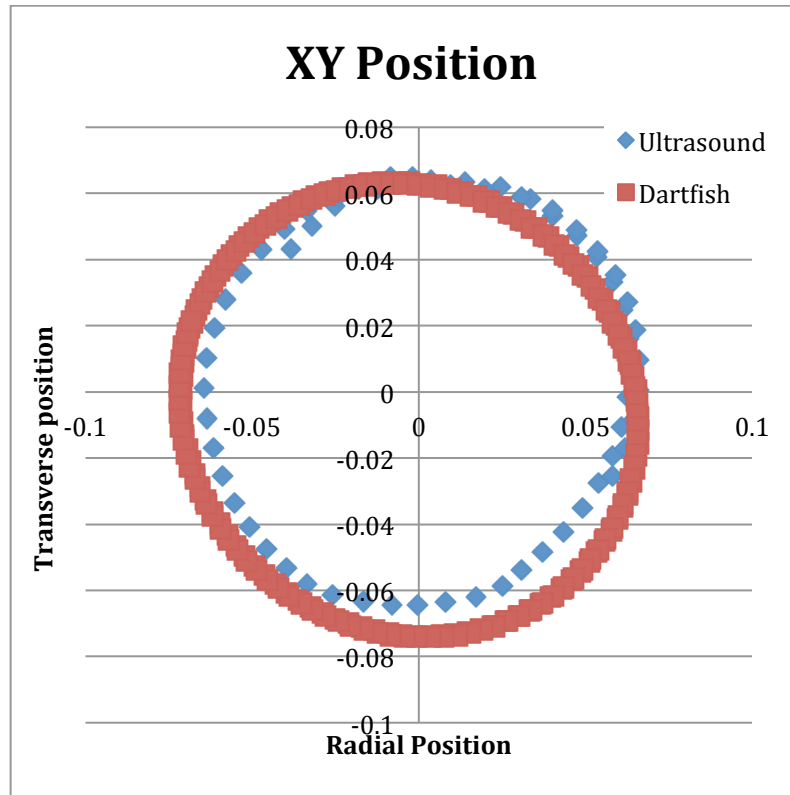


Figure 19: Displaced transducers 45° XY position.

### 5.5.4 Analysis of Off Axis transducers at 45°

Overall, the position data for both the Dartfish and the UDS for the radial and transverse directions match up well as shown in Figure 19. The radial data is defined, in this instance, as the position perpendicular to the line between the two transducers. The transverse position is the perpendicular distance to the left and right of the radial vector. In addition, the Dartfish data is shifted to the left and closer to the transducers. This error may have resulted Dartfish picking out a group of pixels that were not in the center of the battery. Difficulties in maintaining the

same tracking object throughout the motion of the object in Dartfish are common and many times have to be manually corrected as was done in this case.

#### 5.5.5 Transducers Displaced at $22.5^\circ$

The experiment was repeated with transducers 35.6 cm apart ( $a = 35.6$  cm) and 91.4 cm ( $b=91.4$ ) from axis of rotation making  $\theta = 22.5^\circ$ .

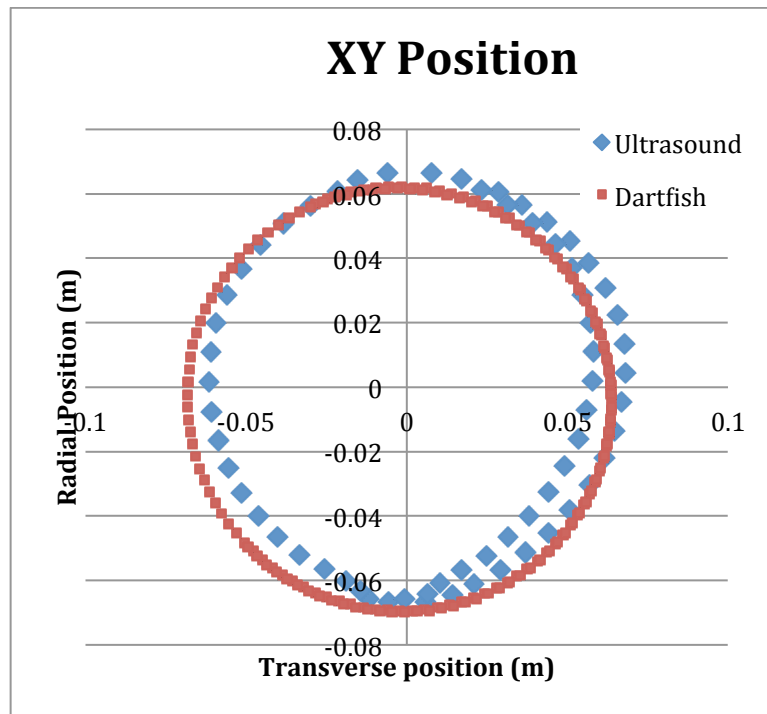


Figure 20: Displaced transducers  $22.5^\circ$  XY position

#### 5.5.6 Analysis of Data with Transducers at $22.5$ degrees

Figure 20 shows that the displaced transducers capture the motion relatively accurately, but the ultrasound data shifts approximately 1 cm during the complete rotation. The shift is due to the algorithm fitting a line to the velocity data in order to take the integral that decreases slightly over time, leading to the 1 cm discrepancy over one rotation. Since the transducers are closer together, it allows for better



measurement of the radial direction and less accurate measurement of the transverse direction.

#### 5.5.6 Transducers Displaced at $135^\circ$

The experiment was tested again with the transducers placed 91.5 cm ( $b = 91.5$  cm) from axis of rotation and 167.6 cm ( $a = 167.6$ ) from one another ( $\theta = 135^\circ$ ).

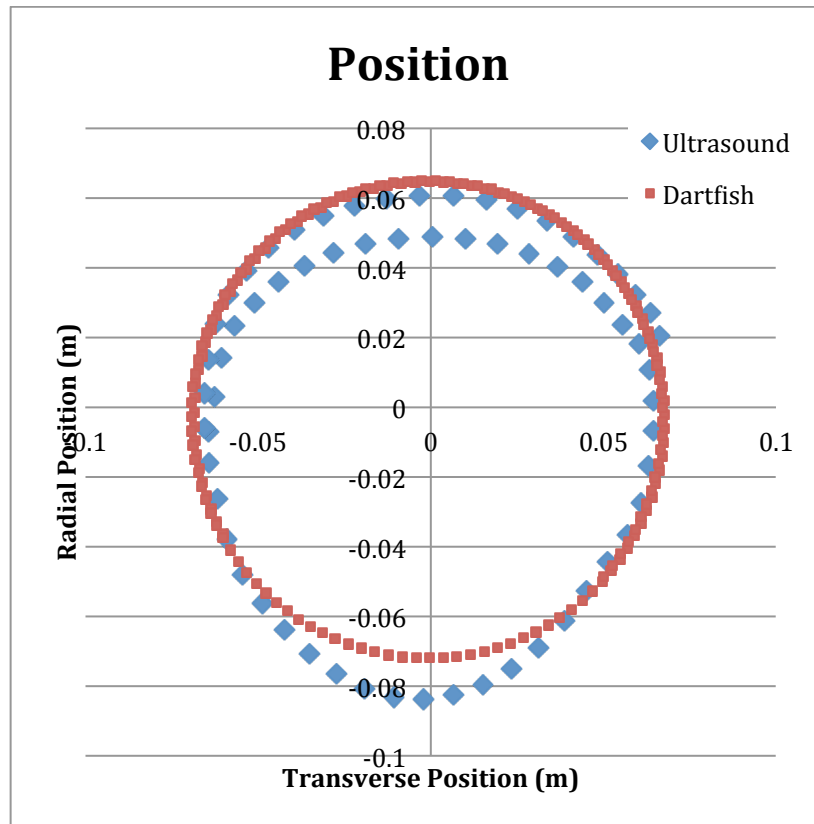


Figure 21: Displaced Transducers  $135^\circ$  XY Position

#### 5.5.7 Analysis

As expected, moving the transducer farther apart causes the transverse position data to be more accurate but the radial direction is less accurate (see Figure 21). Similar to the experiment at  $22.5^\circ$ , the  $135^\circ$  experiment has a shift in the

ultrasound data in the radial direction during a complete rotation due to fitting a sine shaped curve that decreases slowly over time as shown in Figure 21.

## 6. Determining Motion in Three Dimensions using Ultrasonic Doppler Sonar

By adding a third ultrasonic transducer, motion in three dimensions can be determined. Placing all the transducers orthogonal to each other as shown in Figure 22 the motion allows for the simplest method of determining the motion. The electronics setup is the same as Figure 5 except there are three different carrier frequencies, three transducers, three amplifiers and three spectrograms. The code in Appendix E was converted to be able to capture motion in three dimensions (see Appendix G).

### 6.1 Tilted Turntable Experiment

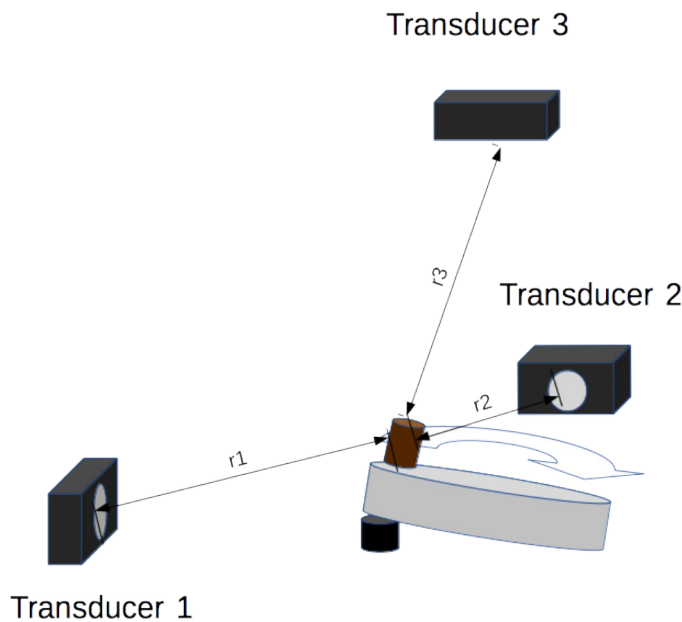


Figure 22: 3D experimental setup for the tilted turntable experiment. The battery was taped to the turntable and a cylinder of two inches was placed beneath the turntable to provide the tilt.

To test the 3-D ultrasonic motion capture system, a turntable was placed with a cylinder under one of the sides that raised the edge of the turntable two inches off the ground. A D battery was taped to the turntable with the distance from the center of the battery to the center of the turntable at 7.5 cm. The turntable was set to 33 rpm and measured for just over one complete rotation. The tilt creates an expected height difference from the lowest point in the circle to the highest point of 2.4 centimeters using two similar triangles one with the hypotenuse as the length of the turntable (31.8 cm) and one using the diameter of the motion of the battery (15 cm).

## 6.2 Results

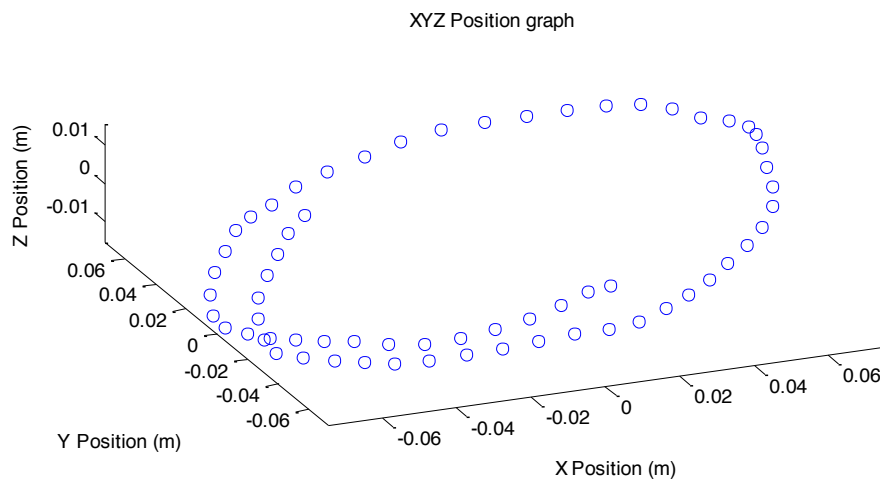


Figure 23: Three-dimensional plot of position of a battery on a tilted turntable

### 6.3 Analysis

From Figure 23, the beginning of the second turn is not lined up with the original turn because the program missed one of the velocity points, therefore skewing the data on the second turn slightly lower than the first. The distance between the maximum and minimum in the z-direction was 3.1 cm. This is greater than the actual value of 2.4 cm and results from the additional velocity perceived by the ultrasonic sensor by the lack of correction for the spherical nature of the waves. A similar system to the displaced two-dimensional system could be developed to correct for this error. The x and y diameters (14.8 cm and 14.5 cm) and were similar to the theoretical diameter for both x and y (14.9 cm).

## 7. Conclusion

This study demonstrates a method of determining 2D motion using UDS and proves the accuracy of this method for both displacement and velocity through a comparison with Dartfish. In addition, the work validates previous work on the accuracy of the UDS motion capture system in one dimension. Further, a method of using the UDS system with off-axis transducers is tested and compared to Dartfish demonstrating its accuracy and limitations depending on where the transducers are placed. The capabilities of UDS are explored with experiments testing objects with different sizes and materials. The geometry of the target object provided the most dramatic effects on the accuracy of the system. Sharp edges create difficulties tracking the object's Doppler shift in the spectrogram. Finally, a demonstration of

the ability of UDS to track motion in 3D is shown. The multidimensional UDS system shows promise to have applications in physical therapy and sports motion capture.

## REFERENCES

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- <sup>4</sup>R. Adebisi, F. Makanjuola, and J.M. Sabatier, "Joint Angle Time History of Human Body Segment Motion," Mid-South ASA Meeting (April 2013) (Unpublished).
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- <sup>7</sup> M. Otero, "Application of a continuous wave radar for human gait recognition," Proc. SPIE 5809, 538-548 (2005).

<sup>8</sup> E. Tucholski, “The Doppler Effect,” <http://www.usna.edu/Users/physics/ejtuchol/documents/SP411/Chapter19.pdf>

<sup>9</sup>M. A. Richards, *Fundamentals of Radar Signal Processing*, (McGraw-Hill, New York, NY, 2005), pp. 92-93.

<sup>10</sup>J. Webster in discussion with the author, June 2015.

## APPENDIX A

To demodulate the FM signal, the carrier frequency is multiplied by the Doppler shifted carrier frequency. This can be expressed by the equation:

$$g(t) \times g_c = \frac{1}{2} [\cos(4\pi f_c t + \phi) + \cos(\phi)]$$

In order to obtain the Q(t) samples the following expression is used:

$$g(t) \times g_{co} = \frac{1}{2} [\sin(4\pi f_c t + \phi) + \sin(\phi)]$$

where  $g_{co} = B \cos(2\pi f_c t - \pi/2) = B \sin(2\pi f_c t)$ . Low pass filtering gives

$$I(t) = \cos(\phi)$$

$$Q(t) = \sin(\phi)$$

After being decimated, the I(t) and Q(t) components are combined to form a complex Doppler signal shown below

$$S(t) = I_{dec}(t) + iQ_{dec}(t)$$

$I_{dec}$  and  $Q_{dec}$  are the decimated I and Q samples and i is the imaginary unit.

The velocity of the moving object is found by using the square of the short-time Fourier transform (STFT), which is given as

$$STFT(t, f) = \int S(t + \tau) w(\tau) \exp(-j2\pi f \tau) d\tau$$

where S(t) is the complex down-converted signal and w(t) is a sliding window function (Hamming window), t is time and f is frequency. The STFT is represented as a time-frequency graph with the horizontal axis as time, the vertical axis as frequency, and the magnitude of the STFT output at each point as the color intensity.<sup>3</sup>



## APPENDIX B

### spec\_wav\_realclock.m

```
close all
clear all

Data= transpose(audioread('test11.wav'));
IF=Data(1,:);
clock=Data(2,:);

n = length(Data);
nfft = 16384;
fs = 100000;
w = nfft/2;
ov = w/2;
c=343;

x1 = 0.0;
x2 = n/fs;
freq_y1 = -500;
freq_y2 = 500;
c1 = -45;
c2 = 50;

fc=40000;
lambda=c/fc;
Nyq=fs/2;

vel_y1=-2;
vel_y2=2;
h=hilbert(clock);
iclock=real(h);
qclock=imag(h);
clear h;
ibase=iclock.*IF;
qbase=qclock.*IF;

R=40;
Rs=0.5;
flc=2000;
flst=4000;

[N,W]=cheb2ord(flc/Nyq,flst/Nyq,Rs,R);
[B,A]=cheby2(N,R,W,'low');

ifilt=filter(B,A,ibase);
qfilt=filter(B,A,qbase);
y=complex(ifilt,qfilt);
[B,F,T]=myspecgram(y,nfft,fs,w,ov);
figure(1);
Clim=[c1 c2];
imagesc(T,F,20*log10(abs(B)),Clim);
axis xy
ylim([freq_y1 freq_y2])
xlim([x1 x2])
```

```

xlabel('Time(s)','FontSize',12);
ylabel('Doppler-Shift(Hz)','FontSize',12);
colorbar();
title('Frequency Graph','FontSize',14)

V=F*lambda/2;
vel_c1=-20;
vel_c2=40;

figure(2);

Clim=[vel_c1 vel_c2];
imagesc(T,V,20*log10(abs(B)),Clim);
axis xy
ylim([vel_y1 vel_y2])
xlim([x1 x2])
xlabel('Time(s)','FontSize',14);
ylabel('Velocity (m/s)','FontSize',14);
colorbar();
title('Velocity Graph','FontSize',16)

```

## APPENDIX C

### positionvtimegraph.m

```
clear
Data = audioread('thepen3.wav');
datatype = 'wav';

t = transpose(1/100000:1/100000:3);
if datatype == 'wav'
    Idata = Data(:,1);
    Qdata = Data(:,2);

    I = Data(:,1).*cos(2.*pi.*40000.*t);
    Q = Data(:,1).*sin(2.*pi.*40000.*t);

    If = myfilter2(I);
    Qf = myfilter2(Q);

    Ifd = decimate(If,20);
    Qfd = decimate(Qf,20);

    td = decimate(t,20);
else
    Ifd = Data(:,1);
    Qfd = Data(:,2);
end

nfft = 2048;
fs = 5000;
w = nfft/2;
ov = w-200;
x1 = 0;
x2 = 5;

y1 = -1000;
y2 = 1000;

c1 = -70;
c2 = 60;

fc = 40000;

c = 343;
lambda = c/fc;

y=conj(complex(Ifd,Qfd));

[S,f,t,jwt,jwv]=myspecgram_jw(y,nfft,fs,w,ov);

figure(1);
Clim=[c1 c2];
Sdb = 20.*log10(abs(S));
imagesc(t,f,Sdb,Clim);
```

```

axis xy;
ylim([y1 y2]);
xlabel('Time(s)');
ylabel('Doppler Shift(Hz)');
colorbar();
position = cumtrapz(jwt,jwv);
a= rms(jwv);
theMax = position(1);
for i = position
    if i > theMax
        theMax = i;
    end
end

theMin = position(1);
for j = position
    if j< theMin
        theMin = j;
    end
end

pos0=(theMax+theMin)/2;

fgposition = position-pos0;

subplot(2,1,1),plot(jwt,jwv, 'o'),xlabel('Time (s)'),ylabel('Velocity
(m/s)');
title('Velocity v. Time Graph'),

subplot(2,1,2),plot(jwt,fgposition,'o'),xlabel('Time
(s)'),ylabel('Position (m)');
title('Position v. Time Graph')

```

## APPENDIX D

### spec\_wav\_realclock2D.m

```
clear all

Data= transpose(audioread('golf1.wav'));
IF1=Data(2,:);
IF2=Data(3,:);
clock1=Data(1,:);
clock2=Data(4,:);

n = length(Data);
nfft = 16384;
fs = 100000;
w = nfft/2;
ov = w/2;
c=343;

x1 = 0.0;
x2 = n/fs;
freq_y1 = -1500;
freq_y2 = 1500;
c1 = -45;
c2 = 50;

fc=40000;
lambda=c/fc;
Nyq=fs/2;

vel_y1=-2;
vel_y2=2;

h1=hilbert(clock1);
iclock1=real(h1);
qclock1=imag(h1);
h2=hilbert(clock2);
iclock2=real(h2);
qclock2=imag(h2);

ibase1=iclock1.*IF1;
qbase1=qclock1.*IF1;
ibase2=iclock2.*IF2;
qbase2=qclock2.*IF2;


R=40;
Rs=0.5;
flc=2000;
flst=4000;

[N,W]=cheb2ord(flc/Nyq,flst/Nyq,Rs,R);
```

```

[B1,A]=cheby2(N,R,W,'low');

ifilt1=filter(B1,A,ibase1);
qfilt1=filter(B1,A,qbase1);

ifilt2=filter(B1,A,ibase2);
qfilt2=filter(B1,A,qbase2);

y1=complex(ifilt1,qfilt1);
y2=complex(ifilt2,qfilt2);


[B1,F1,T1]=myspecgram(y1,nfft,fs,w,ov);
[B2,F2,T2]=myspecgram(y2,nfft,fs,w,ov);


figure(1);
Clim=[c1 c2];
imagesc(T1,F1,20*log10(abs(B1)),Clim);
axis xy
ylim([freq_y1 freq_y2])
xlim([x1 x2])
xlabel('Time(s)','FontSize',12);
ylabel('Doppler-Shift(Hz)','FontSize',12);
colorbar();
title('Frequency Graph','FontSize',14)


figure(2);
Clim=[c1 c2];
imagesc(T2,F2,20*log10(abs(B2)),Clim);
axis xy
ylim([freq_y1 freq_y2])
xlim([x1 x2])
xlabel('Time(s)','FontSize',12);
ylabel('Doppler-Shift(Hz)','FontSize',12);
colorbar();
title('Frequency Graph','FontSize',14)

```

### Appendix III

positionvtimegraph.m

```

clear
Data = audioread('golf.wav');
datatype = 'wav';

t = transpose(1/100000:1/100000:3);
if datatype == 'wav'
    Idata = Data(:,1);
    Qdata = Data(:,2);

    I = Data(:,1).*cos(2.*pi.*40000.*t);
    Q = Data(:,1).*sin(2.*pi.*40000.*t);

    If = myfilter2(I);

```

```

    Qf = myfilter2(Q);

    Ifd = decimate(If,20);
    Qfd = decimate(Qf,20);

    td = decimate(t,20);
else
    Ifd = Data(:,1);
    Qfd = Data(:,2);
end

nfft = 2048;
fs = 5000;
w = nfft/2;
ov = w-200;
x1 = 0;
x2 = 5;

y1 = -1000;
y2 = 1000;

c1 = -70;
c2 = 60;

fc = 40000;

c = 343;
lambda = c/fc;

y=conj(complex(Ifd,Qfd));

[S,f,t,jwt,jwv]=myspecgram_jw(y,nfft,fs,w,ov);

figure(1);
Clim=[c1 c2];
Sdb = 20.*log10(abs(S));
imagesc(t,f,Sdb,Clim);
axis xy;
ylim([y1 y2]);
xlabel('Time(s)');
ylabel('Doppler Shift(Hz)');
colorbar();
position = cumtrapz(jwt,jwv);
a= rms(jwv);
theMax = position(1);
for i = position
    if i > theMax
        theMax = i;
    end
end

theMin = position(1);
for j = position
    if j< theMin

```

```

        theMin = j;
    end
    end
    pos0=(theMax+theMin)/2;

    fgposition = position-pos0;

    subplot(2,1,1),plot(jwt,jwv, 'o'),xlabel('Time (s)'),ylabel('Velocity
(m/s)');
    title('Velocity v. Time Graph'),
    subplot(2,1,2),plot(jwt,fgposition,'o'),xlabel('Time
(s)'),ylabel('Position (m)');
    title('Position v. Time Graph')

```



## APPENDIX E

### positionvtimegraph2d\_jw.m

```
clear
filename = '2d90put1.WAV';

Data = transpose(audioread(filename));
datatype = 'wav';

s1 = demodWav(Data(2,:), Data(1,:), 40000, 100000);
s2 = demodWav(Data(3,:), Data(4,:), 41000, 100000);

nfft = 2048;
fs = 5000;
w = nfft/2;
ov = w-200;
x1 = 0;
x2 = 10;

y1 = -1000;
y2 = 1000;

c1 = -70;
c2 = 60;

fc = 40000;

c = 343;
lambda = c/fc;

[S,f,t,jwt1,jwv1]=myspecgram_jw(s1,nfft,fs,w,ov);
[~,~,~,jwt2,jwv2]=myspecgram_jw(s2,nfft,fs,w,ov);
position1 = cumtrapz(jwt1,jwv1);

theMax1 = position1(1);
for i = position1
    if i > theMax1
        theMax1 = i;
    end
end

theMin1 = position1(1);
for j = position1
    if j < theMin1
        theMin1 = j;
    end
end

pos10=(theMax1+theMin1)/2;

fgposition1 = position1-pos10;
position2 = cumtrapz(jwt2,jwv2);
```

```

theMax2 = position2(1);
for i = position2
    if i > theMax2
        theMax2 = i;
    end
end

theMin2 = position2(1);
for j = position2
    if j < theMin2
        theMin2 = j;
    end
end

pos20=(theMax2+theMin2)/2;

fgposition2 = position2-pos20;

subplot(2,1,1),plot(jwt1,jwv1, 'o',jwt2,jwv2,'+');
title('Velocity v. Time Graph');
ylabel('Velocity (m/s)'),xlabel ('Time (s)');
subplot(2,1,2),plot(jwt1,fgposition1,'o',jwt2,fgposition2,'+');
ylabel('Position (m)'), xlabel('Time (s)');
title('Position v. Time Graph');
figure(34)
plot(-fgposition1,fgposition2,'o');
ylabel('Y Position (m)'), xlabel('X Position (m)');
title ('XY Position graph');
axis square
axis equal

```

## APPENDIX F

### Positionvtimegraph2d\_jw\_displaced.m

```
clear
filename = '2ddispl7.WAV';

Data = transpose(audioread(filename));
datatype = 'wav';

s1 = demodWav(Data(2,:), Data(1,:), 39500, 100000);
s2 = demodWav(Data(3,:), Data(4,:), 40500, 100000);

nfft = 2048;
fs = 5000;
w = nfft/2;
ov = w-200;
x1 = 0;
x2 = 2;

y1 = -1000;
y2 = 1000;

c1 = -70;
c2 = 60;

fc = 40000;

c = 343;
lambda = c/fc;

[S,f,t,jwt1,jwv1]=myspecgram_jw(s1,nfft,fs,w,ov);
[~,~,~,jwt2,jwv2]=myspecgram_jw(s2,nfft,fs,w,ov);

position1 = cumtrapz(jwt1,jwv1);

theMax1 = position1(1);
for i = position1
    if i > theMax1
        theMax1 = i;
    end
end

theMin1 = position1(1);
for j = position1
    if j < theMin1
        theMin1 = j;
    end
end

pos10=(theMax1+theMin1)/2;

fgposition1 = position1-pos10;
```

```

position2 = cumtrapz(jwt2,jwv2);

theMax2 = position2(1);
for i = position2
    if i > theMax2
        theMax2 = i;
    end
end

theMin2 = position2(1);
for j = position2
    if j< theMin2
        theMin2 = j;
    end
end

pos20=(theMax2+theMin2)/2;

fgposition2 = position2-pos20;

subplot(2,1,1),plot(jwt1,jwv1, 'o',jwt2,jwv2,'+');
title('Velocity v. Time Graph');
ylabel('Velocity (m/s)'),xlabel ('Time (s)');

subplot(2,1,2),plot(jwt1,fgposition1,'o',jwt2,fgposition2,'+');
ylabel('Position (m)'), xlabel('Time (s)');
title('Position v. Time Graph');
figure(34)
plot(fgposition1,fgposition2,'o');
ylabel('Y Position (m)'), xlabel('X Position (m)');
title ('XY Position graph');
axis square
axis equal

d1= 1;
d2= 1;

a = .76488;
b = sqrt(d1^2- (a/2)^2);
r1=fgposition1+d1;
r2=fgposition2+d2;
x = zeros(1,length(fgposition1));
y = zeros(1,length(fgposition2));
for i=1:length(x);
    x(i) = (r2(i).^2-(r1(i).^2))./(4*a./2);
    y(i) = sqrt((r1(i).^2 - (x(i)-a/2).^2))-b;
end

figure(35)
plot(x,y,'+');
axis square
axis equal

```

## APPENDIX G

### Positionvtimegraph3d.m

```
clear
filename = '3dturn1.WAV';

Data = transpose(audioread(filename));
datatype = 'wav';

s1 = demodWav(Data(2,:), Data(1,:), 40000, 100000);
s2 = demodWav(Data(3,:), Data(4,:), 41000, 100000);
s3 = demodWav(Data(5,:), Data(6,:), 39000, 100000);

nfft = 2048;
fs = 5000;
w = nfft/2;
ov = w-200;
x1 = 0;
x2 = 3;

y1 = -1000;
y2 = 1000;

c1 = -70;
c2 = 60;

fc = 40000;

c = 343;
lambda = c/fc;

[S,f,t,jwt1,jwv1]=myspecgram_jw(s1,nfft,fs,w,ov);
[~,~,~,jwt2,jwv2]=myspecgram_jw(s2,nfft,fs,w,ov);
[~,~,~,jwt3,jwv3]=myspecgram_jw(s3,nfft,fs,w,ov);
position1 = cumtrapz(jwt1,jwv1);

theMax1 = position1(1);
for i = position1
    if i > theMax1
        theMax1 = i;
    end
end

theMin1 = position1(1);
for j = position1
    if j < theMin1
        theMin1 = j;
    end
end

pos10=(theMax1+theMin1)/2;

fgposition1 = position1-pos10;
position2 = cumtrapz(jwt2,jwv2);
```

```

theMax2 = position2(1);
for i = position2
    if i > theMax2
        theMax2 = i;
    end
end

theMin2 = position2(1);
for j = position2
    if j < theMin2
        theMin2 = j;
    end
end

pos20=(theMax2+theMin2)/2;

fgposition2 = position2-pos20;

position3 = cumtrapz(jwt3,jwv3);

theMax3 = position3(1);
for i = position3
    if i > theMax3
        theMax3 = i;
    end
end

theMin3 = position3(1);
for j = position3
    if j < theMin3
        theMin3 = j;
    end
end

pos30=(theMax3+theMin3)/2;

fgposition3 = position3-pos30;

subplot(2,1,1),plot(jwt1,jwv1, 'o',jwt2,jwv2,'+',jwt3,jwv3, '*');
title('Velocity v. Time Graph');
ylabel('Velocity (m/s)'),xlabel('Time (s)');
subplot(2,1,2),plot(jwt1,fgposition1,'o',jwt2,fgposition2,'+',jwt3,fgposition3, '*');
ylabel('Position (m)'), xlabel('Time (s)');
title('Position v. Time Graph');
figure(34)
plot3(fgposition1,fgposition2,fgposition3,'o');
ylabel('Y Position (m)'), xlabel('X Position (m)'), zlabel('Z Position (m)');
title('XYZ Position graph');
axis square
axis equal

```

## APPENDIX H

### Myspecgram\_jw.m

```
function [y,ff,tt, jwt, jwv] = myspecgram_jw(x,n,sr,w,ov)

if (size(x,1) > size(x,2))
    x = x';
end

s = length(x);

if nargin < 2
    n = 256;
end
if nargin < 3
    sr = 1;
end
if nargin < 4
    w = n;
end
if nargin < 5
    ov = w/2;
end
h = w - ov;

halflen = w/2;
halff = n/2;
acthalflen = min(halff, halflen);
halfwin = 0.5 * ( 1 + cos( pi * (0:halflen)/halflen));
win = zeros(1, n);
win((halff+1):(halff+acthalflen)) = halfwin(1:acthalflen);
win((halff+1):-1:(halff-acthalflen+2)) = halfwin(1:acthalflen);

c = 1;

ncols = 1+fix((s-n)/h);
d = zeros((n), ncols);

I= [];
jwt = [];
jwv = [];
position = [];
i = 1;
figure(2);

myfit = [];

for b = 0:h:(s-n)
    u = win.*x((b+1):(b+n));
    t = fft(u);
    idx = 1:length(t);
    mt = fftshift(t);
    mfft = sqrt(real(mt).^2 + imag(mt).^2);
```

```

    [mmax,I(i)] = max(mfft);
    testrange = [I(i)-5 I(i)+5];
    testdata = mfft(testrange(1):testrange(2));
    xxx = testrange(1):testrange(2);

    [curve, goodness] = fit(xxx',testdata','gauss1');
    myfit = curve.a1.*exp(-((xxx-curve.b1)./curve.c1).^2);
    mfft(testrange(1):testrange(2)) = abs(mfft(testrange(1):testrange(2))-
    myfit);
    [mmax,I(i)] = max(mfft);

    jwt(i) = i*h/sr+.345;
    jwv(i) = -((I(i)-1025)*sr*.0086/(2*n));

    subplot(2,1,1),semilogy(idx, mfft, I(i), mmax, 'ro');
    subplot(2,1,2),plot(jwt,jwv, 'o');
    i=i+1;
    pause(0.2);

    d(:,c) = mfft(1:(n))';
    c = c+1;
end;

figure;

y=fftshift(d,1);
tt = (0:h:(s-n))/sr;
ff=(-n/2):(n/2)-1)*sr/n;

```